[illegible] FOR [illegible] BETWEEN

[illegible] AND ELECTRICITY.

DISSERTATION

[illegible] the [illegible] of University [illegible] the

Johns Hopkins University for the Degree of

Doctor of Philosophy.

by

Norman Everett Gilbert

February 1. 1901.

963

[illegible]

[illegible]

Since the development of the wave theory of light by Huygens in 1678 the most important problem which has confronted the physicist has been the determination of the nature and properties of the medium which we must imagine to fill all space for the propagation of the waves which give rise to the sensation of light. Numerous ethers have been postulated, each with properties which might account for the phenomenon under consideration, but none of which have made any claim to universal application. Green has developed extensively the elastic solid theory and has even made estimates of the density and rigidity of the ether. The recent development of the electromagnetic theory of light and the location of electromagnetic energy in the ether have demanded properties entirely different from any which could be furnished by a rigid elastic solid, and new ethers have been postulated accordingly. Faraday's discovery of the rotation of the plane of polarization of light in a magnetic field suggested that the particles of matter, or the ether in connection with them, must be in rotation. As a result of the theories proposed by Ampere and Weber, and developed by Maxwell, modern theories of magnetism are based on some kind of rotary or

vortical motion of the ether, and if a piece of iron is magnetized, we imagine that the molecules, or something about them, rotate also. Maxwell[1] has tried to detect the presence of any such rotation in an electromagnet. With a kind of gyroscope he showed that, if it exists, the angular momentum must be small compared with any quantities which we can measure. An attempt was made at the suggestion of Professor Rowland by Mr. Paul McJunkin and myself, to determine within what limits it is possible to say that there is no frictional or viscous resistance in the ether connected with such rotation. The existence of permanent magnets shows that any retardation due to any kind of resistance must be very slight.

In the case of an electro-magnet, any energy used in overcoming such resistance, if it exists, must be derived from the exciting current and the disappearance of such energy will produce an apparent resistance added to that of the wire. An attempt was therefore made to determine whether a wire carrying a current had the same electrical resistance when producing a magnetic field that it had when not producing it.

The experiment consisted in winding two coils of wire together on an iron core and determining whether the resistance was the same in two conditions-

1 Maxwell, Treatise, Art. 575

(1) When the current was [illegible] through the coils [illegible] produced a field in [illegible] direction.

(2) When the current was [illegible] arranged that the fields [illegible] counterbalanced each other.

The great difficulty in the experiment lay in the necessity of measuring the resistance of a coil in which a comparatively large current was flowing. In order to overcome the effect of changes in resistance due to changes in temperature, two coils were wound, as nearly as possible identical, and these double coils were used for the four arms of a Wheatstone's bridge so that the temperature would rise in all four arms equally. Each coil consisted of about 2,500 turns of doubled No. 30 copper wire, the whole enclosed in an iron case, boiled in wax for five hours and cooled in a vacuum. The insulation resistance was then about eleven megohms. Iron cores were used and it was found that the cases effectually protected the coils against sudden changes in temperature due to air currents and at the same time served as yokes to the magnets. A current of one-tenth ampere was used which insured a high state of magnetization in the iron when the two coils were in series, giving 5,000 turns.

The coils were connected in the bridge in such a way that the two coils in one case formed the opposite arms

[illegible]

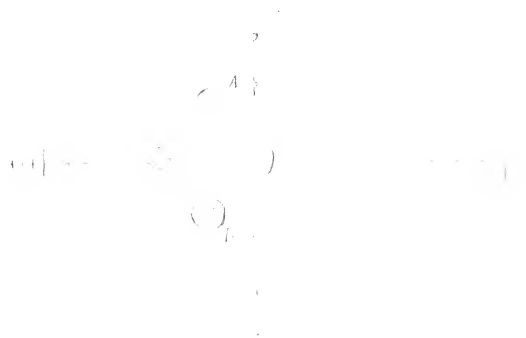

Fig. 1.

[illegible] and [illegible] are the two cases and [illegible] the galvanometer. [illegible] was a reversing switch by which the current in one of the coils could be reversed. This changed the field which might affect two opposite arms of the bridge and thus doubled the deflection. Another switch might have been inserted in the other pair of arms and thus the deflection have been again doubled, but errors due to the switches would also [illegible]

well doubled and no [illegible]. The reversing switch was carefully constructed with [illegible] copper [illegible] fitting into copper mercury cups. The contact of the copper [illegible] that thermal effects [illegible] produced [illegible] appreciable. However, at best, the inaccuracies of the switch limit the accuracy of the experiment.

The fine adjustments were made by a resistance box shunted around one of the coils. About [illegible] ohms in this shunt balanced the bridge. A change of one ohm in the shunt gave a deflection of two millimeters and indicated a change in the resistance of the arm of $\frac{5}{1[illegible]}$ ohm. The whole resistance being over 100 ohms this would give a determination of one part in 2,000,000 or, since the deflection is doubled, one part in 4,000,000 for each arm. The mean of 30 readings each way was that the shunt resistance was about 3.4 ohms less with magnetic field than without. The shunt was so placed that this gives a less resistance by one part in 1,200,000 when producing a magnetic field.

The above result is not in the direction to indicate that any energy is used in maintaining the field. The difficulty may lie in the fact that the galvanometer, though used at night, was unsteady at best, the probable error of the mean being 1.[illegible] ohms, or it may be due to leakage. The resistance of the coils was 100 ohms while the insulation resistance was 11,000,000 ohms. If the leakage is symmetrical

along the coupled wire it will not affect the galvanometer upon reversing the current in one coil, but the assumption that it is symmetrical cannot be justified.

Another important question to be decided by experiment concerns the relative motion of ether and matter. Does the ether immediately surrounding a mass of matter move with the matter in its excursions through space, or does it allow the matter to pass unopposed? Experiments upon this subject give discordant results. If, as the above experiment seems to show, the ether offers no frictional or viscous resistance, we might expect it to remain stationary, allowing the free passage of matter through it. The phenomenon of aberration and the shift of spectrum lines in accordance with Doppler's principle are explained on this hypothesis as well as the fact that no comet has yet shown any acceleration due to ethereal resistance. The elaborate experiments of Oliver Lodge[1], in which he passed a beam of light several times around the space between two rapidly rotating discs, failed to show any difference in the velocity of the beams passing round in opposite directions.

On the other hand the fact that a vibrating molecule can set up vibrations in the ether indicates that there is some sort of frictional connection between the molecule and the ether. Fizeau[2] has shown that when two beams of light,

1. [illegible] p. 7[illegible], 1893.

2. Ann. [illegible] p. 3[illegible], 18[illegible].
A[illegible] Journ. [illegible]

passing in opposite directions through a tube of water, are made to interfere, the fringes are displaced when the water is set in motion, indicating that the ether is carried with the water. His measurements indicated that the water moves a little faster than the ether. Again, Michelson and Morley[1] have made an elaborate series of experiments with their inteferometer, and have been able to detect no displacement of the fringes as the instrument was rotated through different angles with respect to the direction of motion of the earth, thus seeming to show that the ether moves with the earth. Sutherland[2] tried to explain this by showing that the displacement would be too small to be detected, but Lodge[3] dismisses this explanation and suggests that the molecules of the instrument and of the heavy stone slab on which it rests may bear such a relation to the ether that they are compressed along the line of motion and so distort the instrument just enough to balance the effect of the relative motion. Whether or not this explanation is valid it remains for future experiments to decide.

Another method by which this problem may be attacked is to study the nature of electricity and its relation to matter. Maxwell[4] made two interesting experiments along this line. One of them, in which he showed

1 Phil. Mag. Vol. XXIV, p.449, 18[illegible]. Am. Journ. S., 18[illegible], p.47[illegible].
2 Phil. Mag. XLV, p.23, 1898
3 Phil. Mag. XLVI, p. 343, 18[illegible]. 4 E. [illegible] Vol II, sect. [illegible]

that a coil of wire, carrying a current, had no angular momentum due to the current, has already been mentioned. In the other he showed that electricity has no linear momentum since a delicately suspended coil showed no tendency to rotate in its own plane when a current was started or stopped in it. It was while discussing these experiments that Professor Rowland suggested the experiment which we have since carried out. The experiment consisted in trying to detect an electro-motive force generated in a wire wound on the periphery of a wheel in such a way that it would move in the direction of its length when the wheel was rotated. Connection was made to a delicate galvanometer by bringing out the ends of the coil of wire at the centre of the axis, one on either side of the wheel.

Several lines of thought might lead us to expect to find a current in such a circuit when the wheel was rotated. If we consider an electric current to be a continuous giving way of the ether under the action of the electric stresses which, in a dielectric, give rise to electric displacement, then we may think of a moving stream of ether as constituting an electric current, and we might expect that a wire, moving relative to the ether, would have a current generated in it. Moreover we are familiar with several phenomena in which the behavior of positive electricity is very different from that of negative, such as the discharge of negative, but

[illegible] not of positive, [illegible] complete dissimilarity between the phenomena at the electrodes of a Crooke's tube when a discharge is passed through the tube. In practically all of these cases the positive electricity has been shown to be more sluggish in its action than the negative. J. J. Thomson[1] has imagined that ordinary metallic conduction may be only a kind of electrolytic action, in which we might expect the positive electricity to move more slowly or to lag behind the negative in a moving conductor. Such a lag, which is possible without Thomson's hypothesis, would constitute the current for which we are looking. But the consideration which, above all others, has led us to look for such a current is the fact that it would give us at once a simple explanation of the cause of the earth's magnetism. Dr. Schmidt[2], by an extension of Gauss' harmonic analysis, has recently arrived at the conclusion that 9[illegible] 5 [illegible] of the terrestrial magnetism is due to causes within the earth, while Schuster[3] believes that not more than 5 can possibly be attributed to outside causes. This fraction is so small that in the present investigation it may be neglected entirely.

The earliest explanation of this phenomenon, which

---

1. Recent Researches, Art. 34 [illegible] Rapport présenté au Congrès International de Physique. Paris, 19[illegible], p. 138.
2. [illegible] Terre, [illegible] 1[illegible], 19[illegible]. 3. [illegible] Rep. 18[illegible], p. [illegible]

depend upon the existence of permanent magnetism within the earth, must fail since no substance which we know can net in its magnetism at the high temperatures which exist in the interior. In 1879 Ayrton and Perry[1] advanced a theory which depends upon Rowland's experimental proof that a moving electric charge acts magnetically like a current. This theory assumes the presence of a large negative charge of static electricity placed upon the surface of the earth and rotating with it. Rowland[2] successfully disposed of this theory by showing that a surface density great enough to account for terrestrial magnetism would involve a repulsive force sufficient to tear away articles on the surface. To overcome this difficulty Sutherland[3] has assumed that an equal positive charge is concentrated at the centre which will confine the field to the interior of the earth. To keep these charges apart an insulation resistance is necessary which will stand a fall of potential of 2×10^8 volts per centimeter. The high temperature within the earth would destroy the insulating power of most substances which are known at the surface, so that Mr. Sutherland is forced to assume that pressure will counteract this effect and restore the insulat-

---

1 Phil. Mag. VII, p.401, 1879; Proc. Phys. Soc. of London, III, p.57, 1880.
2 Phil. Mag. VIII, p.102, 1879; Proc. Phys. Soc. of London, III, p.93, 18[illegible].
3 Terrestrial Magnetism and Atmospheric Electricity, June, 190[illegible].

ing power. Until we have more evidence on this point it seems that this assumption is hardly warranted. As far back as 1825 Barlow[1] suggested that magnetic polarity might be induced by mere rotation of matter and tried the experiment with iron spheres, but found no effect except that due to hysteresis. In recent years, however, the belief has been gaining ground that terrestrial magnetism is due to the rotation of the earth. Schuster[2], in his presidential address before Section A of the British Association, asks the question "Is every large rotating mass a magnet?" while Lord Kelvin[3] finds it unimaginable but that terrestrial magnetism is due to the greatness and the rotation of the earth, and Professor Rowland has frequently suggested such a cause in his lectures.

If then we may assume that matter by virtue of its motion, has induced in it an electromotive force in the direction opposite to that of its motion, we may proceed to find an expression for the magnetic intensity at a point on the surface of the earth due to such currents in the interior.

Fig. II

1 Phil. Trans. of Roy. Soc. of London 18[illegible], Art. XII.
2 British Association Report [illegible], p. [illegible]34
3 Popular Addresses Vol. [illegible], p. [illegible]

The magnetic potential at a point P due to a current in an elementary circuit is equal to the current multiplied by the solid angle subtended at P by the circuit. Let O be the centre of the earth and the origin of coordinates. Consider first the solid angle subtended at a point P_1 on the axis of the circle which represents also the axis of rotation of the earth.

Let R be the distance of P_1 from the origin

r " " " " circuit from origin

r_1 " " " " P_1 from the circuit

θ " " angle subtended at O by circuit

ψ " " " " " P_1 " "

λ " " latitude of P

Then the solid angle ω at $P_1 = 2\pi(1 - \cos\psi)$

But

$$\cos\psi = \frac{R + r\cos\theta}{\sqrt{R^2 + 2rR\cos\theta + r^2}} = \frac{R + r\cos\theta}{R\sqrt{1 + 2\frac{r}{R}\cos\theta + \left(\frac{r}{R}\right)^2}}$$

$$= \frac{1}{R}(R + r\cos\theta)\left(1 - \frac{r}{R}p_1(\mu) + \frac{r^2}{R^2}p_2(\mu) - \right.$$

where $p_1(\mu)$, $p_2(\mu)$, etc are zonal harmonics

Then

$$\omega = 2\pi\left[\frac{r}{R}p_1(\mu) - \frac{r^2}{R^2}p_2(\mu) + \frac{r^3}{R^3}p_3(\mu) - \right.$$

([illegible])

$- 2\pi \cos \frac{a}{r} - \ldots P_1 (\ldots) + \ldots P_2 (\ldots)$

For a point off the axis introduce the zonal harmonics of the angle $\frac{\pi}{2} + \lambda$)

Then

$$\omega = 2\pi \frac{r}{R} P_1 (\ldots) - \frac{r}{R} P_2 (\ldots \frac{\pi}{2} + \lambda) + \ldots + \lambda) -$$

$$- 2\pi (\ldots) P_1 (\ldots) (\ldots + \lambda) \ldots P_2 (\ldots) (\ldots)$$

if we now move the origin to the centre of the circle,

$\delta = 90°$, $P_1(\delta) = P_3(\delta) = - - - = 0$

$P_2(\delta) = - 1/2$, $P_4(\delta) = 3/8$, etc.

and $\omega = 2\pi \left[\frac{1}{2} \frac{r^2}{R^2} P_1 \left(\frac{\pi}{2} + \lambda \right) - \ldots \frac{r^4}{R^4} P_3 \left(\frac{\pi}{2} + \lambda \right) + \cdots \right]$

which is the ordinary expression for the solid angle at a point subtended by a circle of radius r when the centre is at the origin and $r < R$.

Assuming that the electro-motive force generated is proportional to the linear velocity we may find the current due to the rotation of the earth in an elementary circuit whose centre is on the axis and whose plane is perpendicular to the axis of rotation

Let v be the linear velocity

T the time of rotation

E be the E. M. F. generated in 1 cm. moving at rate of 1 cm. per sec

$\ldots \ldots (\ldots P \ldots 2$

F ... in one circle

... " " current.

" " specific resistance, i.e. the resistance of ... c.c.

m " " magnetic potential due to one circle.

... " " " " due to whole earth.

Then (... II)

$= ... \pi \; r \sin ...$

$... \; \pi ...$

$... = K ... \pi ... = 2\pi K ...$

dr

$m = ... \pi K ...$

$2\pi \left[... P_1(\vartheta) ... P_2(\vartheta) P_1(... + \lambda) + \right.$

$- \cos ... (... P_1(\vartheta) P_1(... + \lambda) + ... \}$

$M = \frac{4\pi K}{...} \int_0^A \int_0^\pi \left[r\left(P_1(\vartheta) \cos\vartheta\right) - ... \left(P_2(\vartheta) ... \right) P_1(... + \lambda) + ... \right]$

since $P_1(\vartheta) = \cos\vartheta$, the first term $= 0$ ... $r^2 ... A$ ...

$\int_0^\pi \left(P_2(\vartheta) - P_1(\vartheta)\cos\vartheta\right) ... \int_0^\pi \frac{1}{2}\left(\cos^2\vartheta - 1\right) ...$

$\frac{1}{...}\left(-\cos^3\vartheta + 3\cos ...\right)\Big|_0^\pi = -\frac{2}{3}$

The remaining terms are of the form

$$\int_0^\pi \left(P_m(\vartheta) \quad P_1(\vartheta) \, P_1 ... \right) d\vartheta$$

where $m > 2$, and each term of this expression vanishes identically. Thus the integral becomes

since

If T_v = the vertical component ... component of the magnetic intensity at a point, we have

(1)

Hence

(1)

where C is a constant defined by the next equation.

(2)

(3)

The values of ... and of ... for ... tions, chosen to represent all parts of the earth, ... in Table I. The values for the intensities are those given by Bigelow[1] in Johnson's Cyclopaedia.

Since ...

1. Johnson's Cyclopaedia, Vol. V ...

culated from the geographic latitudes and longitudes by the well known formula of Astronomy

$$\sin\lambda = \cos\varepsilon \sin l + \sin\varepsilon \cos l \sin b$$

where λ is the magnetic latitude

ε is the polar distance of the magnetic pole

l is the geographical latitude

b is the geographical longitude from the magnetic node.

Owing to the extreme irregularity of the magnetic system it was useless to carry the calculation below the nearest minute, and the nearest quarter degree was used in case of the longitudes. The position used for the magnetic pole was between the values given in 1890 by Neumayer[1] and Schott, i.e. l = 70° 1[illegible]', b = [illegible]3° 30'. This gives for the polar distance ε = 19° 45' and for the longitude of the magnetic node b = 3° 30' W from Greenwich. The values of the constant c agree as well as could be expected in view of the irregularity in distribution of the magnetic elements [owing to unsymmetrical permeability and conductivity in the interior and particularly to local causes of disturbance.] If we give equal weight to the two series of determinations of c as given by the equations $c = F_h / \cos\lambda$ and $3 c = F_v / \sin\lambda$ we obtain a mean value $c = .311$. Substituting this in equation (3) with T = 9[illegible],4[illegible] and A = [illegible]3[illegible].10[5] we have

1 Johnson's Cyclopaedia, Vol. [illegible], p. 46[illegible]

[illegible]				l		λ		F_1	F'	F_h (cos λ)	F
[illegible]	-[illegible]	+ [illegible]	[illegible]'	[illegible]°	44'	[illegible]	54'	.0[illegible]	[illegible]	.[illegible]	.[illegible]
[illegible]	[illegible]	[illegible] 54	0	59	+1	4[illegible]	[illegible]	[illegible]	.4[illegible]	.[illegible]35	[illegible]13
[illegible]	[illegible]	[illegible]	30	[illegible]	29	46	[illegible]	.18100	[illegible]	.[illegible]	.[illegible]
[illegible]	[illegible]	[illegible]	45	4	14	[illegible]	45	.20534	.4[illegible]	.[illegible]4	[illegible]
[illegible]	[illegible]	[illegible]	30	38	[illegible]	[illegible]	20	[illegible]	.5[illegible]28	.3[illegible]	[illegible]
[illegible]	[illegible]-8[illegible]	+1[illegible]	45	34	3	51	[illegible]	.[illegible]78	.4[illegible]00	.4[illegible]	.5[illegible]
[illegible]		-110	2[illegible]	-[illegible]	11	-24	38	.[illegible]7094	-.200[illegible]0	.407	.48[illegible]
[illegible]	-46	- [illegible]	0	33	56	-39	5	.20740	-.27[illegible]76	.[illegible]	.4[illegible]
[illegible]	-63	-1[illegible]	30	-[illegible]7	49	-45	26	.23[illegible]	-.[illegible]409	.33[illegible]	[illegible]
[illegible]	-[illegible]	+ [illegible]	0	-[illegible]	31	-5[illegible]	31	.2[illegible]	-.377[illegible]0	.3[illegible]	[illegible]50

[illegible] = .[illegible]

[illegible] = .[illegible]4

TABLE I.

A 276.71 (10585)

It now remains to determine by experiment whether such a value of the resistances shall give to a reasonable value.

The galvanometer used for this test was one which could be made extremely sensitive, more sensitive, in fact, than it was possible to use in Baltimore. The laboratory has trolley lines on two sides and the B. and O. railway tunnel, in which heavy electric locomotives are used, passes nearly underneath. As a result there were only one hundred minutes daily, divided into three periods between 1:30 and 4 A. M. when the instrument could be expected to be usable, and occasionally entire nights passed without the possibility of obtaining any satisfactory readings. Owing to this cause the progress of the work has been slow and the results at best are unsatisfactory.

The magnetic system of the galvanometer consisted of two sets of magnets, each containing three small magnets about one-eighth of an inch long, mounted on a fine glass thread at a distance apart of about 1 inch. Midway between the two sets of magnets was placed a very small mirror. The inertia of the whole system was thus reduced to a minimum. The suspension was a quartz fibre. Frequent attempts were made, by testing the sensibility in both directions on the scale, to determine whether there was any appreciable torsion in the fibre, but none was detected which was comparable with

outside irregular [illegible] the [illegible] turned through several turns while being more astatic. A magnetic shield consisting of three concentric cylinders of soft iron was used during a part of the time but even with this the galvanometer could be used only during the three quiet periods. It was found advisable to demagnetize the shield occasionally either by heating to a red heat or by placing around it a coil carrying an alternating current and then slowly reducing the strength of the current. By "sensibility" of the galvanometer is meant the current required to give one millimeter deflection when the resistance of the galvanometer (four coils in series) was fifty ohms and the scale was distant one meter. The test current was derived from a dry cell of 1.4 volts E. M. F. cut down by shunts of 10/1400 and 100/10000 and then passed through 10000 ohms in series with the galvanometer. The coil on the experiment wheel was always in series when the sensibility was tested, the resistance being negligible in comparison with the 10000 ohms. The testing system was kept connected so that it could be used at frequent intervals during the progress of the readings and while the wheel was running. The sensibility during the last and best of the readings was kept at 10^{-10}. At this sensibility the galvanometer was "dead beat" and the time required for a single throw, or one-fourth of a complete period was about fifteen seconds. The sensibility could be increased

remove this by first [illegible] the field [illegible] 10^{-11} and on one trial 4.5×10^{-12} was reached. But the time required for a single throw was increased to two or even three minutes and the time required for a complete reading seldom elapsed without a variation in the thermal current or some magnetic disturbance from outside.

At these high sensibilities it is interesting to note that the throw due to a small instantaneous induction current depended directly upon the current, but was practically independent of the sensibility of the galvanometer, showing that the inertia of the system was negligible compared with the damping.

The first attempt to detect an electromotive force due to the longitudinal motion of a wire was made with a coil of rectangular cross section, of No. 30 copper wire, wound in a slot cut in the side of the rim of a wheel. The rim was slit radially to avoid currents in the wheel itself. The mean radius of the coil was 6.25 cms. and the speed was 70 turns per second, giving a linear velocity of 2750 cms. per second. The length of wire was about 42000 cms. and resistance 140 ohms. This wheel was rotated in both directions at a time when a deflection of one millimeter might have been detected, but no reversible deflection of this amount was obtained, though some irregular deflections were obtained due, doubtless, to slight variations in the magnetic

field through the coil. The continuity of the circuit was frequently tested by moving a magnet near the coil and noting the throw due to the induced current. The sensibility of the galvanometer was [illegible] $\times 10^{-[illegible]}$ and the resistance of the circuit 2[illegible] ohms, so that an E. M. F. of 3.[illegible] $\times 10^{-7}$ volts in the circuit, corresponding to $K = 3 \times 10^{-15}$ volts would probably have been detected, though this is by no means certain.

The form of the above coil was not satisfactory. It was enclosed on three sides by brass and the turns on the interior were so shielded by those on the exterior that comparatively few would be exposed directly to the action of the ether if the ether were dragged along as a viscous fluid would be. A new wheel was therefore built whose periphery was a cylinder 4.2 cms. broad and of 7.3 cms. radius. On this was wound in a single layer 175 turns of No. 3[illegible] copper wire giving a resistance of 57 ohms. A test similar to the above was made with this wheel with the result that no reversible E. M. F. as large as $K = 1.2 \times 10^{-14}$ volts was detected. The practical result of these two tests was to show that any E. M. F. which might exist could be detected only by averaging a long series of readings and this was next undertaken.

The sources of difficulty in making these measurements were numerous. In order to insure smooth running at

the high speeds at [illegible] the most reliable [illegible] of the wheel was necessary. The wheel was mounted on a long [illegible] steel shaft which was sufficiently flexible to allow rotation about a true principal axis when high speed was once reached, but trouble was experienced in passing the point at which the speed of the wheel equaled the period of vibration of the wheel on the shaft. Here vibrations became so excessive that the motor was sometimes unable to increase the speed beyond that point. The difficulty was overcome by allowing the cast iron base of the machine to stand unclamped on cotton or on several thicknesses of cardboard, and by most careful balancing. Another source of trouble lay in the thermal currents in the circuit caused by the heating of the copper-silver junctions by the heat flowing away from the bearings when the wheel was running. The terminals of the coil were led out through the end of the shaft in order to avoid as far as possible any friction and consequent heating at the brushes and to reduce to a minimum any alternating currents due to motion of conductors in the earth's field. After running for some minutes the temperature would become approximately steady, but at best the variations in the thermal E.M.F. at the junctions of the wire were much greater than the E.M.F. for which we were looking. These thermal currents were reduced to a minimum by using the same wire, so far as possible, for all connec-

tions. But this could not be done where the circuit passed from the tip of the axis to the brush, for it was necessary to use silver to insure good contact. Silver wires were used for several inches in both directions from the brushes. The contact at the brushes was another source of difficulty. The lead wires were led side by side from the rim to the axis of the wheel, but still a slight alternating current existed sufficient to give a throw of about five millimeters on the galvanometer scale when the wheel was turned quickly through a half turn. This would give no difficulty at high speeds unless the brush were thrown off periodically so as to act as a commutator. This appeared sometimes to occur when the silver tip dug a small cavity in the plane surface of the spring bearing against it. This was overcome by frequently smoothing off the plane surface with a file. This difficulty was so great with copper contacts that it was necessary to use silver as was mentioned above. Another difficulty lay in the fact that the inertia was so great that, though all joints were carefully soldered, earth connections and breaks were frequent at the joints or in the wire itself. These breaks were frequently not complete but simply gave a variable contact and were extremely hard to locate without removing all connections and replacing with new. This was particularly true in the later experiments among the compli-

cated connections of the reversing switch.

The wheel was run by a belt from a one-sixth horse-power electric motor. It was found necessary to keep the frame of the machine in electrical connection with the gas fixture in order to avoid violent throws of the galvanometer needle due to static electricity. The speed first used was 85 turns per second. Later a larger pulley was used giving 125 turns and this was sometimes increased to 150 by shifting the brushes on the motor at each reversal. If this was done after a high speed was reached sparking was not excessive. In the early experiments the motor magnets changed the zero of the galvanometer by about two centimetres. It was impossible to detect any unsteadiness due to the motor when running, but in the later experiments it was moved to the farther side of the room where it had no perceptible effect on the galvanometer.

In taking the readings recorded in table II the wheel was run in one direction while five deflections were taken. Then the motor was reversed by reversing the current in the armature, so as to affect the galvanometer as little as possible, and five more deflections were recorded, and so on. A reading was thrown out if there was any indication that it had been affected by outside influences. The wire was so wound on the wheel that positive electricity lagging behind would pass off the end of the axis away from the pulley

when the wheel was rotating in the positive direction. To determine in which direction this would deflect the galvanometer a small test battery was used consisting of two copper wires to one end of which brass plates were soldered. To the other end of one wire a zinc plate was soldered. The brass plates were separated by a piece of paper and inserted between the silver spring and the tip in the axle, so that the circuit was complete through the test wires. On the zinc plate was placed a moistened piece of paper and this was touched by the copper wire which was connected to the brass plate nearer the galvanometer. Thus the current from this battery passed through the galvanometer in the same direction as a positive current from the wheel. [illegible] this was such, during the first readings in table II as to give a negative deflection. Thus these readings, while very variable, were uniformly in the right direction. The sensibility of the galvanometer was 3×10^{-6}, length of wire [illegible] cms., velocity 3900 cms. per sec. and resistance of circuit 100 ohms. The deflection of .335 mm in each direction would give [illegible] $= 3 \times 10^{-1[illegible]}$ volts. Substituting this in equation (3) we find [illegible] = .94 ohm, a resistance about 3[illegible] times that of mercury. Such a conductivity is easily possible considering the high temperature existing in the interior of the earth and at this stage the experiment appeared most promising.

The experiment was next varied by crossing the lead

[illegible] [illegible]

Speed [illegible]

No.	Temp. readings	[illegible] +	[illegible] -	Diff.	Temp. readings	[illegible] +	[illegible] -	[illegible]
	150	-	-[illegible]	- [illegible]				
1	55	- [illegible]	[illegible]00	- [illegible]				
[illegible]	[illegible]	+ 10[illegible]	+12[illegible]	- 1				
Dec.								
	[illegible]0	- [illegible]	+ 1[illegible]	- [illegible]				
1	[illegible]	+ [illegible]	+[illegible]	+15[illegible]				
[illegible]	[illegible]	- 1[illegible]1	-[illegible]	- [illegible]				
[illegible]	[illegible]	- [illegible]	-[illegible]	[illegible]				
[illegible]	[illegible]	- 24[illegible]	-1[illegible]	- [illegible]				
	[illegible]5			[illegible]				
				[illegible]				

Speed 150 Turns

Jan.					Jd[illegible]			
[illegible]	[illegible]	+ 12[illegible]	+19[illegible]	- [illegible]	[illegible] [illegible]	+[illegible]	+[illegible]	-
[illegible]	[illegible]0	+ 91	+17[illegible]	- [illegible]	6 [illegible]	+ [illegible]	+ 60	[illegible]
					6 [illegible]0	+ [illegible]	+ [illegible]	- [illegible]
[illegible]s [illegible] See opp.					8 50	+1[illegible]4	+11[illegible]	+ [illegible]
					[illegible] [illegible]0	+111	+ [illegible]	+ [illegible]
[illegible]	[illegible]	+ 111	+131	- 20	7 0	- [illegible]0	+ [illegible]	-
[illegible]	[illegible]	- [illegible]	- [illegible]	+ [illegible]				

[illegible]

[illegible]

2	[illegible]	- [illegible]	-312	+ [illegible]	10 [illegible]	-1[illegible]	-2[illegible]	+ [illegible]
[illegible]	[illegible]	- [illegible]	-[illegible]10	+ [illegible]	11 [illegible]0	-2[illegible]	-1[illegible]	-
	[illegible]	- [illegible]	-[illegible]	+ [illegible]	11 [illegible]	-[illegible]	-[illegible]	- [illegible]
	[illegible]			- 2[illegible]	11 [illegible]	-[illegible]	-[illegible]	- [illegible]
				-.04				

[illegible]

- [illegible]
- [illegible]

TABLE II.

wires on the wheel [illegible] at opposite [illegible] of the shaft with the result that the readings failed to reverse properly. The galvanometer terminals were also reversed occasionally, the readings being consistent in every case. The signs have been reported consistently in Table II, so that negative signs with direct wires and positive signs with reversed wires mean currents in the proper direction. These readings were so inconsistent that a reversing switch was devised which was placed directly on the shaft and could be reversed while the wheel was in motion. This device removed the large variations in thermal currents due to stopping the wheel, and eliminated the effects of all electromotive-forces in the circuit except those on the wheel itself, only these being computed. The switch with its connections is shown in Fig. III. The wires from the wheel and from the silver tips in the shaft end in copper springs a, a. Contact is made between these springs by means of two copper plates b, b, mounted on a fibre collar which can be moved along the shaft by a small rod placed in the groove in the movable collar c. The copper springs were properly bent and were controlled by adjusting screws, so that good contact was assured. The complete switch, shown plane in the figure, was cylindrical and was only 3 cms. in diameter, so that the various parts were kept as nearly as possible at the same temperature. The reversing rod w[illegible] the collar

FIG. III.

[illegible] the 15 feet of wire [illegible]. The switch [illegible] but was held firmly in [illegible] the [illegible] of the [illegible] the pressure of the copper springs. The connections of the switch were such that the positive terminal from the wheel was connected to that end of the shaft toward which the switch was thrown. This was verified by passing a current through the machine and noting the deflection of a small compass needle above the wheel. This test was also applied when the wheel was rotating, as an assurance that everything was in order. Another test frequently applied was to pass a current through a delicate milammeter in series with the wheel. The slightest change or unsteadiness in the needle when the machine was started was an indication of trouble.

If a friction exists between the ether and the moving wire, and if there is any viscosity within the ether itself, it is probable that the motion of the wheel would produce convection currents which would greatly reduce the amount of relative motion between the wire and the ether in immediate contact with it. To overcome this as far as possible a copper ring or shield was cast and placed around the wheel. The width of the shield was the same as that of the wheel, the inner diameter three cms. greater than the diameter of the wheel, and the thickness of copper was two cms. The weight was twelve lbs. To eliminate any effect due to the earth's magnetic field the wheel was rotated alternately in and at

[illegible] to [illegible] of the [illegible] measurement [illegible], [illegible] consistent [illegible].

Table III [illegible] the results of [illegible] readings [illegible] this method. Each reading consists of a zero, a deflection given by throwing the reversing switch, and another zero given by throwing the reversing switch back. The galvanometer circuit was kept made thus eliminating the currents which may have appeared in the earlier readings. The galvanometer terminals were reversed by a simple mercury switch. Care was taken to avoid touching any part of the circuit during a series of readings. The sensitivity of the galvanometer was 10^{-9}. The signs have been so adjusted in the columns of differences that positive differences always mean deflections in the direction looked for. The wheel during this series was wound with 8000 cms. of No. 36 copper wire giving a resistance of 1[illegible] ohms in the circuit. The speed was [illegible] [illegible] per second. The average deflection of .[illegible]2 mm. then corresponds to $V = 7.5 \times 10^{-17}$ volt or to $R = .$[illegible]8 ohm, a resistance only 90 times as great as that of mercury. [illegible] the series recorded in Table IV, taken eight months later with a galvanometer ten times more sensitive a deflection of .[illegible] [illegible] in the opposite direction was obtained and this is about sufficient to balance the last. It seems certain, then, that a resistance no greater than 90 times the resistance of mercury would be required for the [illegible]

[illegible] were due t[illegible] [illegible] average specific [illegible] of t[illegible] [illegible]

= 1.23 [illegible] [illegible], [illegible] 500 [illegible]

suggests that [illegible] to [illegible] with currents induced by the currents in the [illegible] atmosphere, which are undoubtedly the primary cause of the short-period variations.

[illegible] has been mentioned an attempt [illegible] of the experiments to reduce possible convection currents in the ether by placing a heavy copper shield around the [illegible] Another attempt to accomplish the same thing was made by placing an electric charge on an insulated brass shield surrounding the [illegible]. Professor Rowland's convection experiment mentioned above proves that a moving charge is accompanied by the ether, thus producing the magnetic phenomena. Conversely, a charge held at rest should hold the surrounding ether at rest. The shield with the [illegible] formed a short cylindrical condenser [illegible] dimensions were

l = 4.3 c.m. = length.
[illegible] = [illegible] " = radius of shield.
[illegible] = 7.[illegible] " = " " [illegible]
d = 0.7 " = [illegible] - [illegible] = distance between the [illegible]
[illegible] = 10[illegible] [illegible] = [illegible] of [illegible]

Th[illegible] [illegible] capacity was

$[illegible] = \frac{l}{2 [illegible]} [illegible]$ 2.84 [illegible]

1 [illegible] P[illegible] [illegible]

[illegible]

[illegible]

[illegible]

[illegible] rs was used to [illegible] in [illegible]. The [illegible] copper wire, single silk covered, [illegible] resistance [illegible] ohms. Owing to some difficulty which [illegible] to locate or eliminate the silver [illegible] were [illegible] moved [illegible] the silver tips in the [illegible] copper wires [illegible] out along the [illegible] ering [illegible] horizontal [illegible] filled with [illegible] entered [illegible]. After several [illegible] run [illegible] the [illegible] deflections [illegible] ent [illegible].

There was [illegible] the electricity from [illegible] wheel was run [illegible]. If [illegible]

[illegible] [illegible] [illegible] [illegible]

[illegible] of [illegible] [illegible]

[illegible], the [illegible] [illegible] [illegible] [illegible]

series of [illegible] [illegible] [illegible] [illegible]

[illegible] of the [illegible] [illegible] [illegible] [illegible]

Jan.	[illegible]			Di[illegible]	
	[illegible]	[illegible]ot	[illegible]	[illegible]	A[illegible]
[illegible]	1[illegible]	[illegible]	+	+ [illegible]	+ [illegible]
[illegible]	1[illegible]	[illegible]	−	+ [illegible]	+ [illegible]
[illegible]	1[illegible]	−	+	− [illegible]	−
[illegible]	1[illegible]	[illegible]	[illegible]	+ [illegible]	[illegible]

The last [illegible] was taken within [illegible], [illegible] accident which necessitated the soldering of the joints [illegible] the [illegible] in the galvanometer circuit, and therefore [illegible] compared with the one above taken on the same night. If, however, we average these readings, [illegible] that the [illegible] of the readings should reverse [illegible] with the direction of rotation [illegible] .17 [illegible] in each direction, [illegible] with that obtained under similar circumstances [illegible]

I [illegible] appreciation [illegible] followed its progress with [illegible] for [illegible] for his [illegible]

[illegible] Everett [illegible]

[illegible] University [illegible]
[illegible], 19[illegible]